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Development of Small-Scale Injection Molding Machine for Biocomposite Material from Agricultural Waste Fibers

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Abstract

Agriculture plays an important role in the Philippines, as it employs a sizable portion of 42.5% of its geographical area. Managing agricultural crop residue in the country is difficult, resulting in environmental pollution. Researchers are investigating the use of agricultural crop residues, such as rice straw and coconut husk, as natural fibers in biocomposites. Combining renewable reinforcement with bio-based matrices, these materials offer manufacturing options.

Injection molding is a promising method for manufacturing high-quality biocomposite materials, but it must be improved to accommodate emergent options. Three different designs were assessed with one undergoing fabrication. In addition, the exploratory experiment was led to determine different independent variables of the product to assess the best fiber-matrix ratio that will conduct in the final experiment. This research seeks to design an injection molding machine capable of transforming agricultural waste fibers and bio-based matrix into biocomposite materials.

Material testing of the injection-molded biocomposite materials is based on ASTM D3039 for tensile testing and ASTM D5229 for water absorptivity. The investigation shows that increasing the mold temperature will also increase the tensile strength of biocomposite material. Moreover, increasing both the mold temperature and fiber ratio will have higher elastic modulus. An increase in mold temperature resulted in a lower elastic modulus. However, increasing the fiber ratio resulted in a higher elastic modulus. The water absorptivity of biocomposites increases with mold temperature and decreases with fiber ratio

due to the hydrophilic nature of thermoplastic starch since the higher starch content leads to a lower fiber ratio.

Keywords: Biocomposite, Fiber, Mold, Matrix, Injection Molding

1. Introduction

Agriculture is a major sector in the Philippines, accounting for 42.5 percent of its land area and 24.2 percent of total employment [1] [2]. Farming is one of the most valuable agricultural sub-sectors, providing major commodities and export products. The rapid and continuous growth of the population necessitates an increase in crop production, leading to the generation of agricultural crop waste such as rice husk, rice straw, bagasse, coconut husk, and coconut shell which is typically disposed of in landfills or by incineration, resulting in environmental pollution and health hazards. [3] [4]. Rice straw and coconut husk are the most prevalent agricultural crop wastes, and efforts are being made to manage and utilize them. Sustainable development and growing demand for renewable alternative materials prompt the use of accessible, affordable, and high-strength rice straw and coconut husk as potential reinforcement for biocomposite material.

The growing interest in developing utilization techniques for agricultural crop residues suggests the reinforcement of natural fibers for biocomposite materials. Biocomposite material combines naturally derived reinforcement and matrix constituents to introduce a new material option with improved properties superior to the performance of its constituents [5]. Natural fibers are typically reinforced with thermoplastics and thermosetting matrices. However, there is rising interest in using bio-based polymers as matrices in biocomposite materials due to environmental issues and the depletion of fossil fuel reserves. Bio-based matrices, such as starch, polylactic acid, and polyoxyalkanoate, derived from renewable sources, are increasingly used as alternatives to matrices derived from petroleum [6]. Depending on the product application and material selection, biocomposite materials can be produced using a variety of processing techniques.

Injection molding is one of the processing techniques employed to produce materials with a high-quality, appealing, and uniform product finish [7]. The appealing design produced by the injection molding machine is perceived as the quality that makes the machine more competitive in the industry [7]. However, the continuous development of injection molding requires technological advancements to process emerging material options [8]. The availability and abundant nature of natural fibers, sustainable and renewable material research explores the application of natural fiber reinforcements in injection molding. However, the reinforcement of fiber throughout the process degrades, necessitating reinforcement of other materials that suit the natural fiber [9]. Additionally, the reinforcement of natural fibers is one of the significant challenges of injection molding as they are thermally sensitive, limiting the matrix material to a relatively low melting point [10]. Natural fibers' preferred matrix constituents are low-viscosity resins due to their ability to impregnate the fiber material easily [11]. These conditions prompted the development of a small-scale

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injection molding machine to process natural fibers derived from agricultural crop waste and bio-based binders into biocomposite material.

The main objective of this study is to design and develop a mechanical device applicable to biocomposite material derived from agricultural waste fibers and to test its functionality as well as the product. The study specifically aimed to 1) design an injection molding machine applicable for turning agricultural crop waste fiber into a more valuable product;
2) explore the parameters of the injection molding machine, such as the mold temperature and different fiber and matrix proportions for more efficient operation and quality of the product;
3) produce biocomposite material from agricultural wastes and assess its mechanical and physical properties.

The study will be significantly beneficial to the farmers by offering a viable solution for utilizing agricultural waste as a raw material to produce biocomposite materials, thereby minimizing the environmental impact associated with waste disposal. The development of this injection molding machine provides innovative ways of material production, offering economic opportunities for the manufacturing sectors. Additionally, the findings of the study will serve as a guide to future researchers for optimizing the processes and technologies of converting agricultural waste into high-quality materials.

This research focused mainly on designing and fabricating an injection molding machine to produce biocomposite material derived from agricultural waste fibers such as rice straw and coconut husk for reinforcement and starch for the matrix. Alkaline treatment will be employed in the preparation of the fibers prior to the injection molding process. The physical and mechanical properties of the biocomposite material produced by the prototype machine will be evaluated under American Society for Testing and Materials (ASTM) standards. The tests of the properties of the injected biocomposite will be limited to tensile strength, elastic modulus, elongation at break, and water absorption. With a limited time, frame, the fabricated machine will be produced on a small scale, manually operated, and based on available resources.

2. Methods

Methodological Framework

The framework (shown in Figure 1) outlines the steps needed to achieve the research objectives and helps ensure that all relevant aspects of the research project are considered. It is divided into four (4) phases namely - ideation, design modeling and assessment, machine development, and product development and evaluation.

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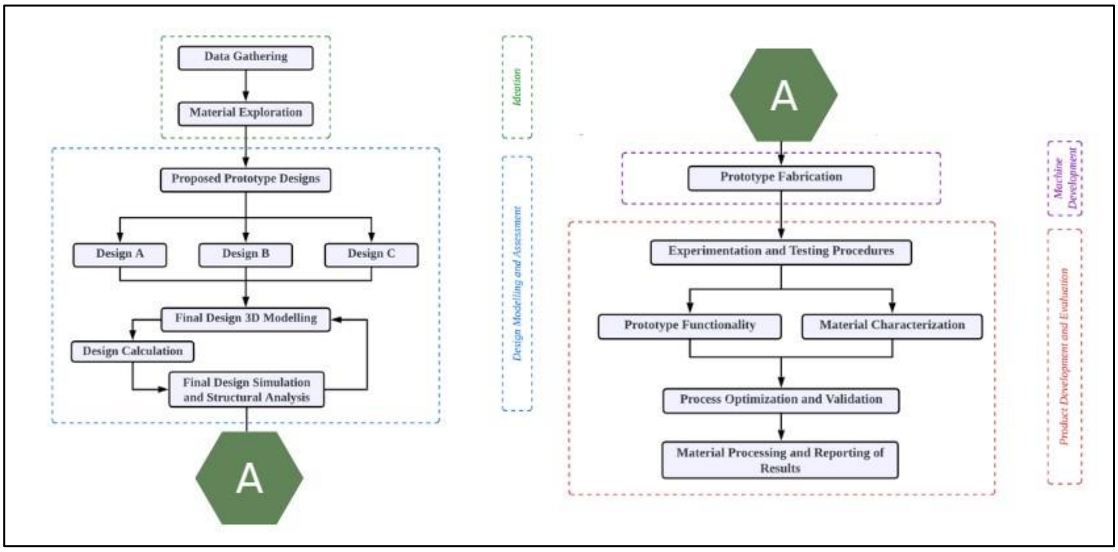

Figure 1
The methodological framework

The ideation phase was primarily the data gathering and material exploration of different methods, treatments, ratios, and processing techniques for biocomposite. Next is the design modeling and assessment phase that provides perspective on the design of the injection molding machine assembly where three (3) designs are considered as candidates for the final design selection. After the selection of the final design, it was followed by the machine development phase. It involves processes such as mold fabrication and assembling of the components of the injection molding machine. Finally, the product development and assessment phase where produced biocomposite materials are tested. Sample specimens are created through the fabricated injection molding machine and subjected to physical and mechanical testing procedures. The results of the experimentation will determine the compatibility of the injection molding machine to process biocomposite material.

Design Requirements

A temperature below 200°C prevents thermal degradation for biocomposite material [12], with a mold dimension range from 3in x 3in x 1in to 6in x 4in x 1in. with a size of the particle of 60 mesh. With the exploratory experiment, the fiber-matrix ratio will range from 20%F:80%M to 30%F:70%M.

Design Options and Evaluation

The design comprises three different options that vary in clamping system and heating unit. Different types of heat transfer principles were concluded, such as conduction, and convection heat transfer. For the clamping unit, it differs from the clamping capacity. Injection units in all designs comprise a barrel, nozzle, and plunger that differ in barrel diameter and stroke. On the other hand, clamping units consist of stationary and moving plates with different types of clamps.

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Three proposed prototype designs, as shown in Figure 2, are considered to determine the most effective injection molding machine.

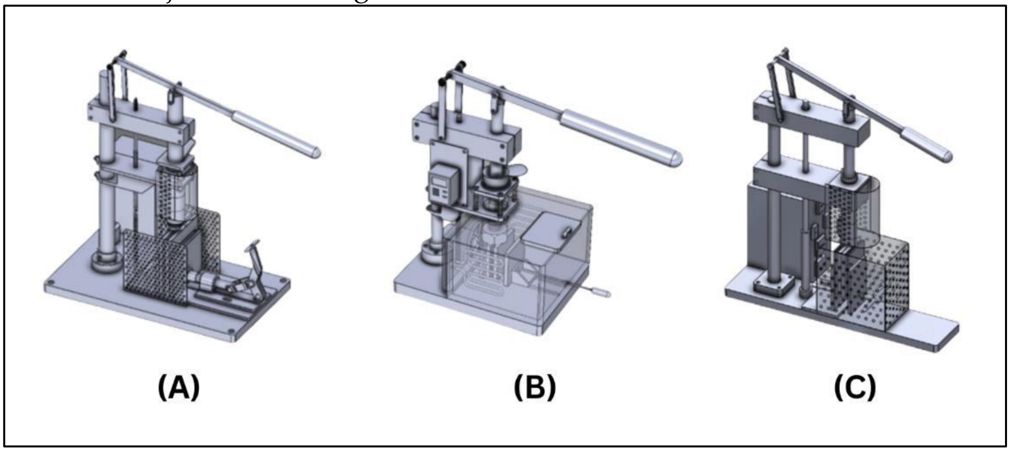

Figure 2

The proposed prototype designs

Design A, illustrated in Figure 2-A, includes a conduction heating system and a toggle clamping unit. A band heater is attached to the barrel. The clamping unit includes a heated mica plate attached to the moving and stationary plates. A toggle clamping unit with a certain plunger stroke is provided to hold the mold. Also, a perforated cover plate is attached to the high-temperature components to serve as protection. On the other hand, since the clamping system uses a toggle clamp the plunger stroke will be limited to a certain range, thus limited sizes of molders will be applicable for the machine.

Design B, shown in Figure 2-B, uses convection heating transfer used as well as a screw type for the clamping system. The heating system is oven-type, consisting of two coils on each side, a fan, and ceramic fiber blanket insulation. Half of the bottom of the barrel and the nozzle are inside the oven. The clamping system of design B consists of a screw clamp. On the other hand, it will be difficult to extract the mold after the cycle since the inside of the oven is small and subjected to high temperatures.

Lastly, Design C, shown in Figure 2-C, comprises a combination of designs A and B with different sizing for injection unit components. Conduction heating system from design A and screw-type clamping unit from design B. The injection unit is also the same as A and B, with the only difference of the hopper is modified based on commercially available technologies. The band heater is placed concentrically for the heating system, with the barrel and mica plate attached to the holding plate. It also comprises two temperature controllers for each heating system.

In summary, the evaluation of various designs and calculations reveals that design C is the most optimal, effective, and balanced in terms of convenience. This model's conduction-type heat transmission is more efficient than design B's oven-type heating system, and its barrel diameter is smaller than that of design A, resulting in a lower power requirement. In addition, its smaller inner diameter allows for a more uniform thermal distribution of biocomposite material throughout the injection phase. Consequently, the specifications and

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performance of Design C are optimal for guaranteeing the production quality of the biocomposite products.

Materials and Fabrication Procedures

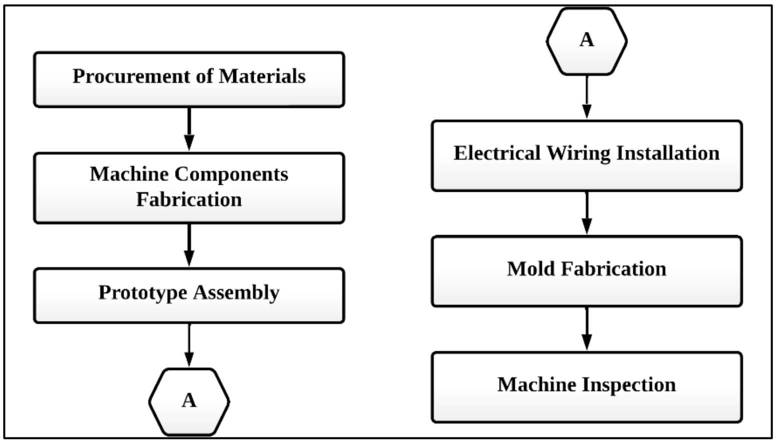

Figure 3

Fabrication procedure of the injection molding machine

The fabrication of the machine is divided into stages illustrated in Figure 3. The first stage is the procurement of commercially available materials with the right specifications based on the calculation and final design. The next stage is machine components fabrication. A local and accessible machine shop is tasked with fabricating the required dimensions of each component. It will then be followed by prototype assembly, where the welding process will be done to assemble the machine components and the installation of the injection and clamping unit to the base frame. The subsequent step is the installation of the electrical wiring. After the machine construction, mold fabrication took place that matched the specification of the machine. The last stage will involve machine inspection to determine if the quality of the machine corresponds to the requirements.

Experimental Design and Procedures

Various factors are considered and determined whether they are dependent, independent, or extraneous variables, as shown in Table 1.

Table 1

The variables of the study

Independent Variables	Dependent Variables	Extraneous Variables

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Fiber-to-Matrix ratio Molding temperature Thermoplastic starch ratio Sun-drying time Oven drying time Oven drying temperature	Fiber size Alkaline treatment concentration Barrel temperature Molding time Barrel capacity Mold size	Tensile strength Elastic modulus Elongation at break Water absorptivity	Ambient temperature Relative humidity Force exerted by the person tasked

A 2k factorial design is employed to explore and determine the relationship between the experimented independent and dependent variables. Utilizing a 22-factorial design, two levels and two factors are considered to anticipate a valid result from the defined variables. The two factors have an equivalent of four samples and 4 center points multiplied by two replicates, yielding twelve (12) specimens for injection-molded biocomposite materials. It will minimize experimental biases and ensure the consistency of the results. The factorial design employed for the study is presented in Figure 3.

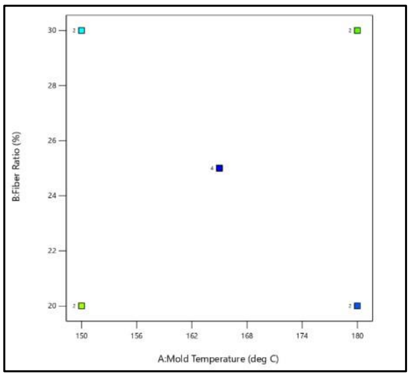

Figure 4

The 2^k factorial design for injection molding of biocomposite material

The fibers used in the study, rice straw and coconut husk, are mixed for even distribution. Each sample of biocomposite mixture will be randomly injected into the injection molding machine. The equipment used, from preparing the raw material to processing, is uniform in controlling other factors. Instruments used to process materials are of the same brand and specifications. Furthermore, the injection molding procedure will be done only by the assigned personnel and strictly in the designated place to minimize experimental error and ensure the uniformity of the biocomposite material.

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The fabricated injection molding machine processes the biocomposite material specimen for material property testing. A fabricated injection mold is used to accurately produce the specified dimensions of the specimen according to the standard for tensile testing of polymer matrix composite materials (ASTM D3039). The tensile testing of the injection molded specimen will be conducted using a Universal Testing Machine (UTM). The water absorptivity of the injection-molded biocomposite material will be conducted according to the standard test method for testing the moisture absorption properties of polymer matrix composite materials. The American Society for Testing and Materials (ASTM) standard to be used is the ASTM D5229. The typical specimen size specified by this testing standard has a 100 mm x 100 mm dimension. Initially, the dry weights of the injection-molded biocomposite materials are measured and collected. The data will be processed to calculate the percentage of water absorbed by the injection-molded biocomposite specimens using the defined formula shown in Equation 1.

$$\%W = \frac{(W_{wet} - W_{dry})}{W_{dry}} \; x \; 100\% \qquad \text{Equation 1}$$

where: %W = water absorbed by the specimen (%)

W_{wet} = wet weight of the specimen (g)

W_{dry} = dry weight of the specimen (g)

Results

Final Equipment Design

Among the three alternatives, design C was chosen as the most reliable design. This prototype design consists of a screw clamping device, a conduction heating system composed of a band heater and a mica plate heater, and a control system with two temperature controllers. The stated design has dimensions of 900 x 710 x 305; however, the actual dimensions are 814 x 612 x 150 due to the limited amount of material available and the fabricator's suggestions for the sizes of the various parts, who has knowledge and experience in fabricating various types of machines, that will still result in optimal performance of the machine's capability.

Figure 5

The perspective view of final design

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Tabulated Results

The tensile specimens of biocomposite material are fabricated according to ASTM D3039. Each sample is randomly injected using the prototype machine and tested using the Universal Testing Machine. After a series of runs, the gathered data are processed using Microsoft Excel, Origin Pro, and Design Expert.

The biocomposite specimen is fabricated according to the ASTM standard for testing the water absorptivity of polymer matrix composite (ASTM D5229). The behavior of the biocomposite material with moisture is obtained by calculating the amount of water absorbed by the material specimen soaked for 30 minutes at room temperature. Using the formula for water absorptivity, table 1 presents the summary of results for the mechanical and physical properties of rice straw and coconut husk biocomposite material.

Table 2

Summary of results for rice straw and coconut husk

Molding Temperature (°C)	Fiber Ratio (%)	Max. Tensile Stress (MPa)		Elastic Modulus (MPa)		Water Absorptivity (%)	
		Rice Straw	Coconut Husk	Rice Straw	Coconut Husk	Rice Straw	Coconut Husk
150	20	3.09681	6.7572	45.3523	309.135	49.345	40.969
180	20	3.72875	3.8163	81.5732	183.441	95.370	52.711
150	30	3.00096	4.64351	163.777	343.699	32.673	24.264
180	30	4.10341	8.15649	256.902	646.352	67.195	42.693
150	20	2.28149	7.72746	66.1734	321.18	41.681	41.317
180	20	3.82077	6.12549	93.8965	196.564	95.069	47.449
150	30	3.841	7.91683	176.41	390.021	39.674	27.882
180	30	5.11449	10.5475	290.947	650.864	65.693	47.244
165	25	2.18756	5.00736	81.8589	348.599	51.784	38.868
165	25	1.74832	5.35849	76.3749	370.143	59.301	37.616
165	25	2.97433	4.93032	76.8601	321.748	55.586	39.015
165	25	2.54371	6.47403	97.628	348.927	51.913	37.148

3. Discussion

The model graph, illustrated in Figure 6, depicts the 3D model graph of the interaction between factors of injection-molded rice straw specimens. The maximum tensile strength of

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the biocomposite material reinforced with rice straw increases as the mold temperature increases. The increase in tensile strength is a result of the fiber's inherent strength and the removal of moisture from the biocomposite material. The optimum tensile strength of a biocomposite material increases proportionally with mold temperature.

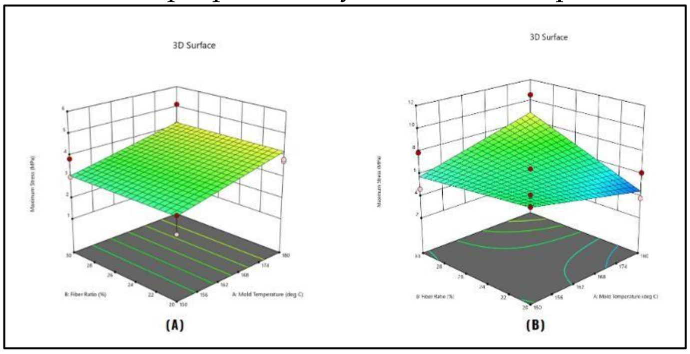

Figure 6
The 3d model graph for maximum tensile strength of (a) rice straw and (b) coconut husk

The relationship between the mold temperature, fiber ratio, and elastic modulus is presented in Figure 7. The elastic modulus of the biocomposite material reinforced with rice straw increases with mold temperature and fiber ratio. The increase in elastic modulus is caused by the removal of moisture and the inherent fiber strength. On the other hand, the elastic modulus of the coconut husk-reinforced biocomposite material increases with the fiber ratio but decreases with mold temperature. The impurities of coconut fiber led to diverging results of elastic modulus and mold temperature as the fiber-matrix ratio increases.

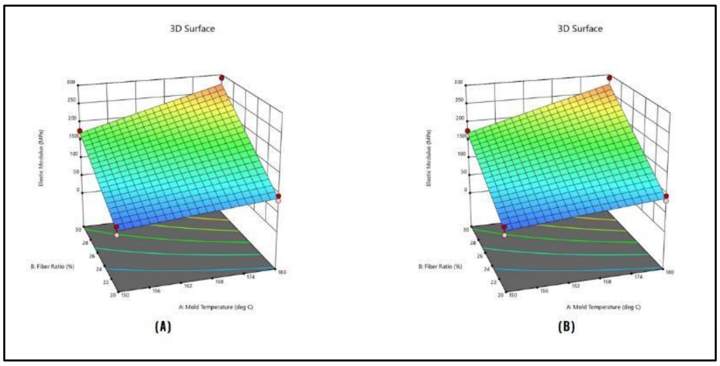

Figure 7
The 3d model graphs for elastic modulus of (a) rice straw and (b) coconut husk

The correlation between the factors (mold temperature and fiber ratio) and water absorptivity is described using a 3D model graph generated using Design Expert Software. Figure 6 shows the 3D model graphs of rice straw (A) and coconut husk (B).

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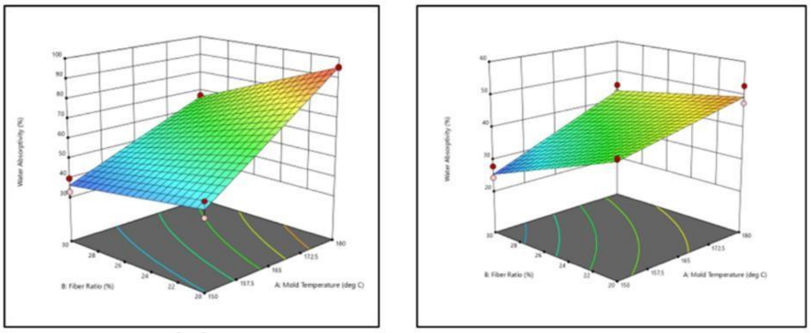
As shown in Figure 5-A, the water absorptivity of rice straw biocomposite material increase with temperature. However, the water absorptivity decreases as the fiber content of the rice straw biocomposite increases. The same trend is described in Figure 5-B for coconut husk biocomposite material. The highest water absorptivity of rice straw-reinforced biocomposite material is obtained on a sample with 180°C mold temperature and 20% fiber ratio having an average numerical value of 95.2195%. Similarly, the highest data for water absorptivity of coconut husk biocomposite material is obtained at 180°C mold temperature and 20% fiber ratio, with a 50.08% value.



(A) (B)

Figure 8

The 3d model graph for water absorptivity of (a) rice straw and (b) coconut husk

Regression Analysis

The relationship equation between the significant factors for rice straw and coconut husk is described in this section. This equation will determine the predicted values of dependent variables considering both the accommodated units for each run. As a result, table 2 summarizes the relationship equations of the factors to the dependent variables such as maximum tensile strength, elastic modulus, and water absorptivity.

Table 3

Summary of model equations

Maximum Tensile Strength of Rice Straw
$Max.\ Tensile\ Strength = 0.037893A - 2.62888$
Elastic Modulus of Rice Straw
$Elastic\ Modulus = 385.83216 - 3.72487A - 24.49647 + 0.239530$
Elastic Modulus of Coconut Husk
$Elastic\ Modulus = 4906.5555 - 31.29569A - 198.28113 + 1.35634B$
Water Absorptivity of Rice Straw
$\%\ WA = 2.62868A + 8.78398B - 0.064786AB - 334.77847$
Water Absorptivity of Coconut Husk

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$$\% WA = 85.54211 - 0.150077A - 5.98664B + 0.029864AB$$

where: A = Mold Temperature in deg Celsius (°C)
B = Fiber Ratio in %

4. Conclusion and Recommendation

In conclusion, the paper summarizes the research findings, discusses implications and future development, and highlights the significance of the research. Design C was found to be the best among the three alternatives, featuring a conduction heating system. The prototype was designed to maintain the molten state of the biocomposites during injection. Two types of specimens were produced for testing, evaluating water absorption and tensile properties using ASTM standards. The data collected shows that water absorption increases with mold temperature but decreases with fiber ratio. Therefore, higher ratios of thermoplastic starch to fiber result in greater water absorption capacity. Mechanical properties have been tested to observe the capability of the biocomposite product. Study shows that increasing the mold temperature will also increase the maximum tensile stress of the biocomposite material. Moreover, increasing both the mold temperature and fiber ratio will have higher elastic modulus. An increase in mold temperature resulted in a lower elastic modulus. However, increasing the fiber ratio resulted in a higher elastic modulus.

This study examines the viability of producing biocomposite materials with a manual vertical injection molding machine. It illustrates the effectiveness of the manufacturing procedure by highlighting the ability to withstand injection pressure and clamping force. The prototype represents an alternative method of production with eco-friendly benefits, reducing waste and carbon emissions. The research indicates the possibility for additional development and innovation. Recommendations include optimizing the machine by enhancing components such as the clamping unit, barrel coating, and plunger closure, as well as investigating various fiber-matrix ratios for increased versatility.

5. References

A. Rudin and P. Choi. (2013). *"Chapter 13 - Biopolymers," in The Elements of Polymer Science & Engineering (Third Edition),* ScienceDirect, 2013, pp. 521-535.

A. S. Mohite, A. R. Jagtap, M. S. Avhad and A. P. (2022). "*Recycling of major agriculture crop residues and its application in polymer industry: A review in the context of waste to energy nexus,*".

Briefing, A. S. E. A. N. (2017). *Biomass industry in the Philippines.*

www.bpsu.edu.ph/PIJIS
ISSN 3028-1725 (Online)
Vol II, No.1, 2024
www.bpsu.edu.ph
Doi 10.5281/zenodo.12729743

Feldmann, M., & Fuchs, J. (2016). Injection molding of bio-based plastics, polymers, and composites. In *Specialized Injection Molding Techniques* (pp. 211-237). William Andrew Publishing.

H. Fu, Y. Liu, H. Xu, Z. Yang, S. Kormakov and J. Sun. (2020). *"Overview of Injection Molding Technology for Processing Polymers and Their Composites,"* ES Materiral & Manufacturing.

J. Gim and L.-S. Turng. (2022). *"A review of current advancements in high surface quality injection molding: Measurement, influencing factors, prediction, and control*," Polymer Testing.

Leong, Y. W., Thitithanasarn, S., Yamada, K., & Hamada, H. (2014). Compression and injection molding techniques for natural fiber composites. In *Natural Fibre Composites* (pp. 216-232). Woodhead Publishing.

PM, M., EC, M., & CAM, R. (2012). Utilization of agricultural wastes in the manufacture of composite boards. *ASEAN Journal on Science and Technology for Development*, *29*(2), 129.

Rabbi, M. S., Islam, T., & Islam, G. S. (2021). Injection-molded natural fiber-reinforced polymer composites–a review. *International Journal of Mechanical and Materials Engineering*, *16*, 1-21.

Statista Research Department, "Agriculture in the Philippines - Statistics & Facts," Statista, 2022.

The World Bank, "Agricultural Land (sq. km) - Philippines," The World bank, 2020.

Thomason, J. L., & Rudeiros-Fernández, J. L. (2021). Thermal degradation behaviour of natural fibres at thermoplastic composite processing temperatures. *Polymer Degradation and Stability*, *188*, 109594.